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Large crack tip deformations and plastic crack advance during fatigue

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Abstract

Finite-deformation elastoplastic analysis of a crack subjected to mode I cyclic loading under small scale yielding was performed. The influence of the load range, load ratio and overload on the crack tip deformations is presented. Cyclic crack tip opening displacements agreed with predictions of simpler models, where available. Crack closure was not detected. Plastic crack advance was evidenced. Its rate per cycle reproduced common trends of the fatigue cracking dependence on loading range and overload.

Keywords: Fatigue; Computer simulation; Crack tip; Crack closure; Crack growth rate

1. Introduction

Fatigue was considered the cause of 90% of mechanical failures, which has been keeping this issue in the fore for decades. Fatigue proceeds by nucleation and growth of cracks until rupture. Analyses of the crack tip deformations (displacements), strain and stress fields are valuable for understanding the crack behaviour. Their in situ monitoring is hardly feasible, and simulations seem to be the right way to determine them. Account for both physical (material's) and geometrical (large deformations and strains) nonlinearities is essential for realistic implications for fracture. Among available analyses of cracks, some, including otherwise comprehensive ones devoted to fatigue, such as Ref. [1], have not accounted for large deformations, whereas others [2–6], although fulfilling this deficiency, have been confined to the monotonic loading or presented limited data about the cyclic one.

This work was focused on deformations near the crack tip under fatigue aiming to advance towards resolution of the long-standing controversy about plasticity-induced crack closure [7,8], and to elucidate relevant effects, such as the Laird's scheme of plastic crack growth or the role of overload [7].

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2. Modelling

Finite-deformation simulations of the crack tip fields in elastoplastic material were performed for a straight plane-strain crack subjected to mode I loading under small scale yielding (SSY), i.e., all nonlinearities were localised in a small near-tip domain, so that the stress intensity factor (SIF) K could be the governing variable. This principle of SIF-dominated autonomy of the near-tip zones and justification of its applicability to fatigue were outlined elsewhere [7].

At large strains, material strain-hardening approaches saturation. Then, material idealisation by elastic–perfectly-plastic model can be acceptable. The ideal elastoplastic solid having Young modulus E, Poisson ratio ν and yield strength σ_Y with von Mises yield criterion and associated flow rule was chosen. Material characteristics were typical for a variety of materials: $\sigma_Y/E=0.003$, $\nu=0.3$. The model of undeformed crack was a parallel-flanks slot of the width b_0 and semicircular tip, as substantiated previously [2–4]. As designed elsewhere [4], the entire model was symmetric double-edge-cracked panel under remote tension, where K-dominated SSY was enforced.

The near-tip situation in rate/time-independent materials under SSY is governed by peak values of SIF, the maximum K_{max} and minimum K_{min}, and the cycle number N. Simulated load cases consisted of up to ten cycles at different constant amplitudes and load ratios $R=K_{min}/K_{max}$, and the effect of a single overload was considered, too:

(I) $K_{max}=K_0$, $K_{min}=0$;
(II) $K_{max}=2K_0$, $K_{min}=0$;
(III) $K_{max}=2K_0$, $K_{min}=K_0$;
(IV) $K_{max}=K_0$, $K_{min}=0$ with an overload to $K_{ov}=2K_0$ in the sixth cycle.

Large-deformation elastoplastic solutions were generated using a finite-element code with updated Lagrangian formulation. The mesh and incremental analysis procedure were as outlined elsewhere [4].

3. Results and discussion

For all four load cases, near-tip deformations proceeded similarly, such as shown in Fig. 1.

The crack tip opening displacement (CTOD) δ_t used to be the key variable of the near-tip fracture process zone [2–4,7]. Although "operational" CTOD definitions are somewhat arbitrary, the discrepancies between them under monotonic loading are minor [2,7]. In fatigue, more hazy deformation patterns (Fig. 1) may cause a deficiency of CTOD as a crack tip characteristic. Here a usual definition of CTOD [2] was adopted as twice the y-displacement of the point B_0 in Fig. 1.

Cyclic CTOD trajectories $\delta_t=\delta_t(K,N)$ were dependent on K_{max} and K_{min}, and slightly influenced by N (see Fig. 2, where $\delta_{max}(1)=\delta_t(K=K_{max}, N=1)$ and $\delta_{ov}=\delta_t(K=K_{ov})$). Confirming K-dominance conditions, these plots for similar load cases I and II were identical. Ratcheting of $\delta_t(K,N)$-trajectories vanishes with N, and they converge to stationary loops. At monotonic loading phases and during constant-amplitude cycling, CTOD paths agree with numerical and analytical models [2–4,7], where available. For the load case IV (Fig. 2c), the bottom envelope of the $\delta_t(K)$-plot from the loading start towards the absolute SIF maximum K_{ov} is fairly the same as the monotonic-load trajectories in Fig. 2a,b, but interrupted by load cycling. The post-overload $\delta_t(K)$-loops, in comparison with the pre-overload ones, only shift upwards depending on the K_{ov} magnitude.

Thus, in the context of capability to monitor damage accumulation towards the local rupture or to provide correlations with crack growth trends, CTOD is not much more advantageous than SIF. In particular, it provides no insight into the post-overload crack retardation.

Plasticity-induced crack closure as a contact of its faces upon unloading was raised as a rationale for fatigue predictions with account for various factors affecting crack growth, such as variable SIF amplitude, over- or under-load peaks, etc. [7]. Having had advocates and opponents [7,8], it remains a controversial matter. Simulations presented herein provide high-resolution data about deformed crack shape, which agree in pertinent aspects with other results [1–3,7]. However, crack closure was never detected. Although the crack upon unloading acquired a keyhole shape shrinking in a wake behind the tip (Fig. 1), deformed crack width did not return to b_0. This contradicts the results of small-displacement simulations [1] in which, however, not only deformation but also bond-breaking events were involved.

Deformed meshes in Fig. 1 reveal the mechanism of material transfer from the crack front onto lateral faces of the crack, as evidences a neighbourhood of the point B_1 in Fig. 1. There material "bricks", initially situated a little bit beside the top A_0 of the tip-forming arc $B_0B_1A_0$, move sideways and convert into crack flanks. Plastic straining of these bricks with

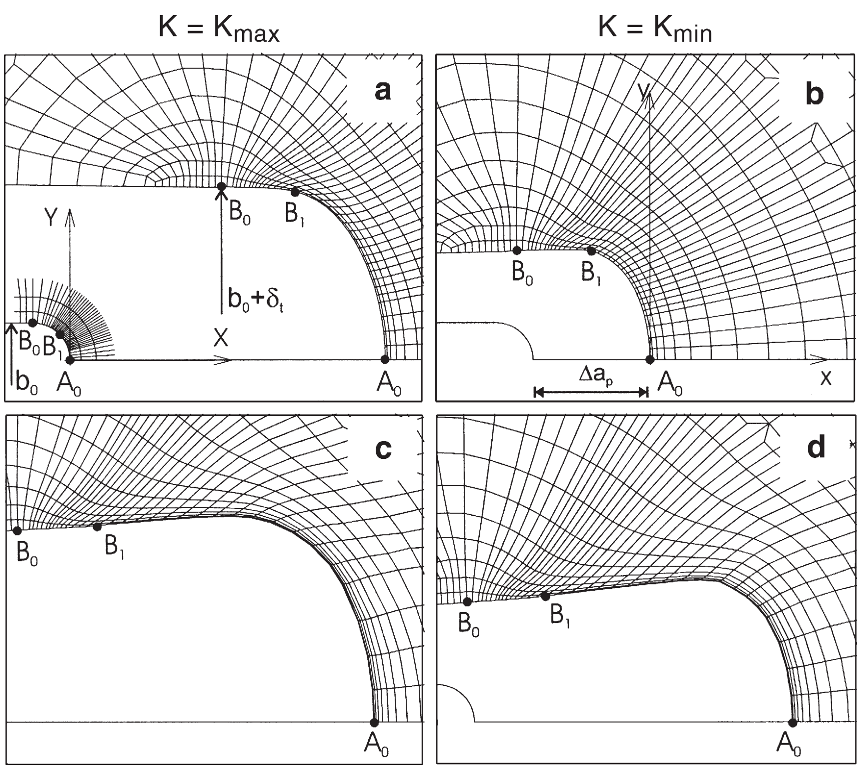

Fig. 1. Crack tip deformations at K_{max} and K_{min} for the load case II: (a) and (b) — at high- and low-peak loads of the first cycle; (c) and (d) — the same of the fifth cycle. Symmetric half-specimen is shown; undeformed configurations of the mesh (fragment) and tip contours are seen in the bottom-left corners in (a), and in (b, d), respectively.